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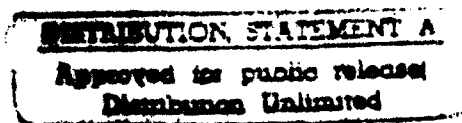
Final Report

Prepared For

Office of Naval Research
800 North Quincy St.
Arlington, VA 22217

By D. L. Davidson

Southwest Research Institute
P.O. Box 28510
San Antonio, TX 78228-0510

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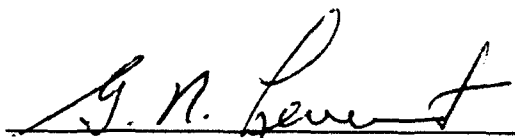N00014-85-C-0206

Prepared For:

Office of Naval Research
800 North Quincy St.
Arlington, VA 22217

By:

D. L. Davidson

APPROVED:

Gerald R. Leverant, Director
Materials and Mechanics Department

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This final report summarizes research on the fatigue and fracture toughness of a large number of materials ranging from metallic and ceramic matrix composites reinforced with ceramic particulates to aluminum, titanium and glass matrix composites reinforced with continuous fibers. The purpose of this report is to summarize and draw conclusions about the state of knowledge of fatigue and fracture mechanisms from the past several years of research sponsored mainly by ONR.

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David L. Davidson	(210) 522-2314	

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MICROMECHANISMS OF FATIGUE CRACK GROWTH AND FRACTURE TOUGHNESS IN METAL AND CERAMIC MATRIX COMPOSITES

I. EXECUTIVE SUMMARY AND INTRODUCTION

This report summarizes in a broad way conclusions I have derived from research at SwRI, most of it sponsored by ONR, from reading the literature, and as the result of participating in a number of conferences on composites, both in the USA and Europe. In the course of this work, four review articles (three proceedings papers [1-3] and one book chapter [4]) have been published, in addition to other publications that have detailed specific research results.

A broad range of composites has been investigated during the period covered by this contract. The following materials were studied:

(1) aluminum alloys reinforced with irregular particles of SiC and alumina, and spherical particles of alumina/mullite,
(2) Saffil reinforced aluminum alloys,
(3) partially stabilized zirconia,
(4) the aramid fiber reinforced aluminum alloy ARALL,
(5) Nicalon fiber reinforced CAS glass,
(6) titanium alloys reinforced with SCS-6 fibers,
(7) silicon nitride reinforced with SCS-6 fibers.

Research on composites 2, 4 and 5 was not performed directly as a part of the ONR contract, but the results are applicable to the main thrust of the research topic and have contributed to either the depth of understanding of composite fracture or to the breadth of applicability of the conclusions given in this report.

Each section of the report covers one class of materials. Conclusions drawn from research on that composite are listed in that section.

II. RESEARCH OBJECTIVES AND METHODOLOGY

Although the range of composites studied has been broad, the research goals have remained relatively narrow. Research has focused answers to the following questions: (1) What are the mechanisms by which fatigue cracks grow and what mechanisms contribute to measured fracture toughness? (2) Can fracture mechanics be used to describe the fatigue and fast fracture characteristics of these composites? (3) what is required to predict the fracture behavior of composites?

The techniques of experimental micromechanics, as developed at Southwest Research Institute, have been used extensively in the research, together with more standard techniques, such as fractography and transmission electron microscopy.

III. ALUMINUM ALLOY MATRIX COMPOSITES

A. PARTICULATE REINFORCED:

The most systematic and thorough investigation of fracture properties was done for aluminum alloys reinforced with irregular particles of SiC and alumina. The materials were chosen for investigation in order to: (1) compare differences in matrix composition and heat treatment, (2) compare the effect of SiC volume fraction, and (3) compare differences in particle size. Materials were supplied from two different companies: Novamet and Dural Aluminum Composites Company (now Duralcan). The combinations of matrix alloys and SiC characterized were:

Al-4Mg+15v/o SiC   2014+15v/o SiC   2014+25v/o SiC

2024+15v/o SiC   7475+15v/o SiC   IN-9052+15v/o SiC

The Duralcan Al-4Mg+15v/o SiC cast and extruded composite was used to compare directly with the Novamet mechanically alloyed and extruded IN-9052+15v/o SiC [5]. Composites with the 2000 and 7000 series matrices were evaluated in both as-received and peak-strength ageing conditions. Particulate used in both these matrices was single crystal SiC.

A small amount of work was also performed on 6061-T0 and -T6 reinforced with spherical polycrystalline alumina/mullite particles approximately 7 μm in diameter. This material was made by casting and extrusion by the Commonwealth Aluminum Co. in Australia and is referred to as Comral-85.

Saffil reinforced Al-7Si-0.6Mg and Al-5Si-3Cu-1Mg matrix composites manufactured by squeeze casting were investigated in connection with Prof. Claude Bathias for clients in France. Saffil is a matte of alumina fibrils approximately 3 μm in diameter that are interconnected and bonded to give a "preform" into which aluminum alloys were squeezed under pressure.

Microstructures: Characterization of microstructures was accomplished with great expenditure of time and effort. Light microscopy, scanning electron microscopy and transmission electron microscopy were all used. It was discovered during the process of characterization that the clumping of particles was a microstructural feature for which no standard measurement technique exists. Several research groups are working on characterizing clumping, but there is still no method in general use. The mechanical properties of these composites is highly dependent on the characteristics of the particles (size distribution, strength, clumping), matrix (intermetallic particles, strength, ductility) and the fabrication and quality control techniques used. However, when research results are reported in the literature, these constituent properties are usually not reported, or poorly characterized at best.

Conclusion: Much of the published data potentially useful to an understanding of fatigue and fracture toughness does not have much value due to an incomplete characterization of the materials investigated.

Fatigue Crack Initiation: The initiation of fatigue cracks was not directly studied during this contract, but data from the literature indicate that fatigue crack initiation in particulate reinforced composites is a function of the following material characteristics: (1) surface finish, (2) particle clumping, (3) the presence of intermetallics in the matrix, (4) particle size (large particles are likely to be broken or to break easily), and (5) matrix strength. Initiation may be dependent on environment for some matrices, and it is dependent on R ratio. For Saffil reinforced materials, the fatigue limit is the result of small cracks that initiate but do not grow. For other composites, the fatigue limit is probably controlled by the initiation of cracks (depending on what definition is used for "initiation").

Conclusion: An understanding of fatigue crack initiation depends strongly on microstructural characteristics, which are a product of the manufacturing technology and quality control used during material fabrication. The depth of understanding of material fatigue crack initiation characteristics depends on the methods and thoroughness used during material characterization.

The Growth of Large Fatigue Cracks: Fatigue crack growth in all the composites studied was by intermittent crack advance. However, few striations were found during fractographic examination [5,6]. At some levels of ΔK, microcracks formed near the main crack, and it was possible through micromechanics analysis to show that these had very little effect on the stress intensity of the main crack. Measured strain distributions were found to be significantly altered by the close proximity of SiC particles, particularly at low ΔK [6], but otherwise, strain distributions were found to be similar at all the values of ΔK studied. This finding agreed well with the concept

that the threshold was controlled by particle-limited slip in the matrix, but that the similitude normal for fatigue crack growth in monolithic metals was essentially preserved in the composites at intermediate levels of ΔK.

Fatigue crack growth rates in all these materials could be characterized using the Paris relation (the manifestation of similitude):

$$da/dN = B\Delta K^s \tag{1}$$

and a value of ΔK_{th} was measured for each composite [7]. Measurements of crack closure using the direct method of observing crack opening in the SEM confirmed that the trends found for monolithic alloys also applied to the composites. This result indicated that closure for large fatigue cracks could be determined, as it can in monolithic metals, from

$$\Delta K_{eff} = \Delta K - \Delta K_{th} \tag{2}$$

With this relationship, eq. (1) can be rewritten as

$$da/dN = B'\Delta K_{eff}^{s'} \tag{3}$$

Correlations were found between the coefficients B and s in eq. (1), as they have for other materials (mainly steels), and a correlation was found between ΔK_{th} and s. Thus, universal values of B' and s' were derived that described fatigue crack growth for a large range of composites [7].

A simple model based on the size and volume fraction of particles was used to compute ΔK_{th}:

$$\Delta K_{th} = (1-R)\sigma_y\sqrt{2\pi r_s} \tag{4}$$

where σ_y = yield stress and r_s = the slip distance at the crack tip, calculated as the mean-free-path (MFP) for dislocation motion through the composite. MFP may be computed from the mean size and volume fraction of particles.

Values of ΔK_{th} calculated using this simple formula correlated well with those measured for the alloys studied, and it also correlated reasonably well with values of ΔK_{th} measured by other investigators for similar composites. Therefore, by knowing the microstructural characteristics of a new (untested) composite, it should be possible to predict, or at least estimate, the fatigue stress intensity threshold using eq. (4), and the fatigue crack growth rate curve using eq. (3) with the derived values of B' and s', solely on the basis of microstructure.

Conclusion: The growth of large fatigue cracks in these composites is similar to monolithic alloys and may be predicted on the basis of microstructure, strength and semi-empirical relations.

Growth of Small Fatigue Cracks: Some data exists in the literature on the growth of small fatigue cracks in these composites. The most systematically derived data found to date came from Cambridge University, and these data have been examined in the context of the growth of small fatigue cracks in monolithic alloys. Small fatigue cracks in the composites, as with monolithic alloys, grow at values of ΔK below the large crack threshold; thus, there is a "small crack effect." For monolithic alloys, direct measurements of crack closure and crack tip plasticity have shown that the main difference between small and large fatigue cracks is the level of crack closure [8]. For small cracks

$$\Delta K_{eff} = \beta \Delta K \qquad (5)$$

where $\beta \approx 0.46$, a constant regardless of alloy. When the growth rates were compared on the basis of ΔK_{eff}, the correlation between large and small crack using eq. (3) was excellent; thus, all the data collapsed onto one line.

Conclusion: The growth of rates of small cracks can be predicted on the basis of the growth rates of large fatigue cracks for these composites. This is the same as was found for monolithic alloys.

<u>Fracture Toughness:</u> The mechanically alloyed IN-9052 matrix composite was found to have the lowest fracture toughness ($K_c \approx 9$ MPa√m) of all the materials tested. The physical characteristics of this material may be summarized as follows [5]: strong matrix-particle interfaces, bimodal particle distribution, but with a fairly good particle dispersion, a large volume fraction of intermetallic particles (Al_4C_3, Al_2O_3 and MgO), and a subgrain size of about 0.67 µm. The material exhibited a fairly large porosity. Fast fracture occurred with the formation of few dimples, but a few large broken SiC particles (probably precracked) were also found. At the point of fast fracture, strain distribution was measured and a model for computing the work expended in forming the plastic zone was derived. This plastic work term, W_p, was related to K_c through the modified Griffith equation: $K_c = \sqrt{(W_p E)}$, and through this process it was found that the stress intensity at fast fracture could be accounted for by the plastic work done during fracture.

This modeling effort led to a method for examining the mechanisms of fracture for many materials. By determining the plastic work expended in fast fracture, an assessment of the effectiveness of other proposed mechanisms of fracture may be examined; e.g., crack bridging, fracture of SiC particles, and microcracking ahead of the main crack tip.

The ingot produced 2014 matrix composite was found to have the highest fracture toughness, although quite a range in toughnesses were measured by repeating tests ($K_c \approx 18$ to 28 MPa√m) [9]. The physical characteristics of this material may be summarized as follows: strong matrix particle interfaces, particle distribution with peak at 6.6 µm, and with a fairly poor particle dispersion; e.g., many clumps of SiC were found. Some interface separation occurred within clumps, presumably due to insufficient working which breaks up oxides at the matrix-particle interfaces and allows adhesion to occur. There was also 0.03 volume fraction of intermetallics, mostly containing copper, some as large as 20µm in size [9]. No quantitative method was found for characterizing the clumping found in this material.

Tensile tests were performed in the SEM [9] and it was found that particle clumping had a large effect on the magnitude of strains within the matrix, and that these were found to greatly exceed the overall elongation measured for the specimens.

Just as for the mechanically alloyed composite, fast fracture occurred with the formation of few dimples, and a few large broken SiC particles (perhaps precracked) also were found [9]. At the point of fast fracture, strain distribution was measured and the previously developed model for computing the work expended in forming the plastic zone was used. Again, it was found that the stress intensity at fast fracture could be accounted for by the plastic work done during fracture. Crack bridging, which occurred during one of the fast fracture experiments, was found to be completely ineffective [9].

Goolsby and Austin [10] made a general survey of K_c values reported in the literature and found that $K_c \approx 15 \pm 6$ MPa√m, except for very thin specimens. This similarity in fracture toughness of this large number of composites is remarkable given the differences in matrix alloy and

reinforcement it encompasses. Somersby, et al. [11] reviewed the theories for predicting fracture toughness (actually, rationalizing measured values) and concluded that none of the theories adequately described these composites. They concluded that fracture toughness is a poorly understood subject, in general, and that is especially true for particulate composites.

> **Conclusion:** The factors controlling fracture toughness are not well understood in these composites. There are effects of particulate clumping, the presence of intermetallics, particulate strength, and matrix strength that are not addressed by the theories of fracture toughness. For an unknown composite from a reliable manufacturer, assuming that fracture toughness $\approx 15 \pm 5$ MPa$\sqrt{m}$ would be reasonable.

Fracture surface roughness: The magnitude of fracture toughness for steels has been correlated with surface roughness, so a similar link was sought for these composites. There has also been speculation about a correlation between ΔK_{th} and fracture surface roughness. Fracture surface roughness was measured for fracture surfaces generated by both fatigue and fast fracture [12]. Roughness was found to be described very well by the fractal dimension for both cases. However, no correlation was found between fracture surface roughness and either ΔK_{th} or K_c for these composites. Upon further investigation, the reasons for this result became more apparent, in that the mechanisms by which crack growth is occurring in these materials is influenced in only a minor way by the resulting crack path.

Breakage of SiC particles has been raised as an issue with these materials by many investigators, but, in general, this mechanism has not been determined to be much of a factor in controlling fracture, either fatigue or fracture toughness. One reason for fracture of the large SiC, at least for the case of the mechanically alloyed composite, was that these particles were often cracked during processing [5]. Good quality control during manufacture should largely eliminate particle fracture as an issue in these composites.

In some studies, no microvoids were found in the fast fracture regions, indicating that little energy was being absorbed by microvoid growth and coalescence. However, for other composites, small microvoids are reported. In the absence of microvoids, tear ridges have been found - these may be viewed as large, disconnected "microvoids" which are unorganized, but the main point is that tear ridges cover less area that the regions of large plasticity which surround an extensive, well developed microvoid system; thus, the energy expended in forming these tear ridges is low. The energy of microvoid formation was estimated by a model developed in [5] and found to be at least a factor of 10 less than that expended in forming the crack tip plastic zone. Surprisingly, no other model for energy expenditure during void formation has been found in the literature.

> **Conclusion:** The fracture toughness of aluminum alloy matrix particulate reinforced composites are controlled principally by two factors: (1) the toughness of the matrix, and (2) the limitations on slip imposed by the particles. So far as could be measured, fracture toughness and the fatigue threshold were not controlled by crack bridging, trapping of cracks at particles, microcracking, or the breakage of particles. The general concepts controlling fracture toughness which have come from this work were summarized in the chapter [4] of a book, and a recent review paper [1] has examined some of the other issues related to fracture of these composites.

Particle Shape: Commonwealth Aluminum Co. in Australia makes a material referred to as Comral-85 that is reinforced with spherical polycrystalline alumina/mullite particles approximately 7 μm in diameter. Since the particles are spherical, this material is fundamentally different from all the other composites that have been examined. A small fracture study was undertaken because a theoretical study [13] indicated that particle shape was likely to strongly affect the fracture behavior of the composite due to differences in constraint on the matrix alloy deformation, which was 6061-T0 and -T6 for the composites studied. The primary effort was undertaken by Mr. Greg Heness of University of Technology, Sidney, as part of his Ph.D studies, while he was on

sabbatical at Southwest Research Institute in early 1993.

The particles in this composite were found to be weak, breaking readily near the crack tip in the peak aged material (-T6 temper, $\sigma_y \approx 330$ MPa), but for the -T0 material ($\sigma_y \approx 55$ MPa), no particle fracture was experienced. However, even with particle fracture (-T6 temper), fracture toughness values were above average; $K_c \approx 19$ MPa$\sqrt{m}$. For the -T0 temper, $K_c \approx 25$ MPa$\sqrt{m}$.

Constraint, as measured by the ratio of mean strain to effective strain in the matrix, was indeed found to be a function of particle shape, with the region between spherical particles exhibiting the least constraint. Constraint in the irregular particle reinforced material was more uniform and generally higher.

For a Duralcan material with approximately the same volume fraction of irregularly shaped particles as Comral 85 and the same matrix alloy, $K_c \approx 22$ MPa$\sqrt{m}$. Thus, although the differences in constraint caused by particle shape were clearly demonstrated, fracture toughness levels appear to be more sensitive to yield stress and particle strength than on the constraint of matrix deformation.

This study again emphasized the limited knowledge we have about the factors controlling fracture toughness in this and other materials, and our ability to predict this important parameter. Thus, we do not have the ability to design microstructures to obtain desired levels of fracture toughness.

Conclusion: The shape of particles does, in fact, alter the level of matrix alloy constraint in aluminum alloy matrix composites, but this is not the factor that controls the toughness. Matrix cleanliness and strength and particle strength appear to control fracture toughness. However, if the matrix were made tougher, then perhaps particle constraint would become more important.

Conclusion: Historically, the fracture toughness of particulate composites has been $\approx$ 15 MPa$\sqrt{m}$, but with better quality control, values of ≈ 25 MPa$\sqrt{m}$ have been obtained recently. The limiting (attainable) toughness of these composites appears to be ≈ 30 MPa$\sqrt{m}$ because of the limited toughness of the aluminum alloy matrices. This compares very well with the toughness of conventional aluminum alloys.

Saffil Reinforced Aluminum Alloys: Fatigue crack initiation at ambient temperature and fracture toughness at 25 and 200°C were investigated. The general result, not yet reported in the literature, was that reasonable fatigue crack initiation properties for specimens with carefully prepared surfaces were achieved. Broken Saffil fibrils were found to exist on the first loading cycle; subsequent loading could cause these cracks to grow into the surrounding matrix for a short distance, but then these cracks stopped. From this work, it is concluded that the fatigue limit, as in steels, is controlled by whether or not cracks grow rather than by the initiation of cracks.

Fracture toughness of these composites was found to be fairly low and was not a function of temperature up to 200°C; above that temperature, creep dominated fracture was observed. Plasticity of the matrix was found to quantitatively account for the level of toughness measured. The methods used for this assessment are explained in refs. [4,5].

B. CONTINUOUS ARAMID FIBER REINFORCED ALUMINUM ALLOYS:

The material investigated (for General Dynamics Corp.) was ARALL-4, which had a matrix of 2024-T8 aluminum alloy sheets interspersed with layers of 12 μm diameter Kevlar 49 fibers embedded in epoxy with a density of about 860 fibers per layer per mm of material width, giving an overall volume fraction of fibers of about 15%, which is approximately the same as the volume fraction of reinforcement in the particulate composites studied. Fatigue crack growth direction was

perpendicular to the fibers [15].

Crack closure was extensively measured, but crack growth at intermediate rates (10^{-8} m/cy and higher) in the composite could not be derived from crack growth rates in the matrix alloy by adjusting for the differences in closure. The extraordinary damage tolerance of this material is caused by bridging of the crack by unbroken aramid fibers. Recently, the ARALL crack growth data were again analyzed using the same model for crack bridging as used for the Ti-6Al-4V/SCS-6 composite [16], and the crack growth rates were successfully predicted on the basis of crack growth rates through the matrix alloy [3].

Conclusion: Fatigue crack growth through a broad range of metal matrix composites, where crack bridging is the dominant mechanism, can be predicted using proven fracture mechanics concepts.

IV. SCS-6 FIBER REINFORCED TITANIUM ALLOY COMPOSITES

Fatigue crack growth perpendicular to fiber direction was extensively studied at ambient temperature in a Ti-6Al-4V matrix composite made with the foil-fiber-foil technique by Textron Specialty Materials and donated by General Electric Aeroengines. Center notched specimens loaded in tension were used for this work because the poor transverse strength of this material caused only crack growth parallel to fiber direction from single edge notched specimens loaded in tension. This material was found to be extremely resistant to the growth of fatigue cracks under constant amplitude loading because of extensive bridging of the crack by unbroken fibers.

Comprehensive micromechanics measurements were made from this composite. The parameters measured were: fatigue crack growth rate as a function of load level and crack length, the minimum load crack opening displacement (COD) that resulted from matrix-fiber debonding, COD at maximum load, and fiber strains and crack tip deformation at maximum load. The theoretically derived fracture mechanics model of Sneddon and Lowengrub was found to describe crack growth rate and was compatible with all of the parameters measured. Conversely, the modeling concepts that require load transfer through fiber-matrix interfacial friction did not describe the results obtained [16].

Similar results were obtained at ambient temperature for a composite with Ti-14Al-21Nb reinforced with SCS-6 fibers, also manufactured by the foil-fiber-foil technique by Textron [17].

Experiments are underway with the Ti-6Al-4V with SCS-6 fiber reinforcement at 600°C in vacuum to determine if the micromechanics at this elevated temperature are the same as at ambient temperature.

Conclusion: A relatively simple fracture mechanics approach may be used to calculate fatigue crack growth rates at ambient temperature in SCS-6 reinforced composites with several titanium matrices that are controlled by crack bridging mechanisms. Frictional interface models are not applicable for fatigue crack growth in these alloys. Because of similar results for the ARALL composite, it appears that this approach may be used on a broad range of composites that exhibit crack bridging.

Crack bridging models will not be predictive until a good model is derived for fiber fracture. That model does not now exist, and there is insufficient published data to derive it. The research on crack bridging has been successful at stresses well below those that designers would like to use in gas turbine applications. Thus, it is not clear that bridging is applicable to actual use conditions.

V. CERAMIC MATRIX COMPOSITES

A. PARTIALLY STABILIZED ZIRCONIA (PARTICULATE REINFORCED)

The confusion amongst ceramists about fatigue crack growth in ceramics, voiced at a Gordon Conference, led to a relatively small study of fracture in partially stabilized zirconia [18]. This material has been described as a matrix of cubic zirconia in which small precipitates of tetragonal zirconia are dispersed; thus, it may be considered as a type of particulate reinforced composite. Deformation converts the tetragonal precipitates to the cubic phase with an accompanying change in volume that alters the residual stresses in the material. Crack growth processes, particularly by fatigue, should be considerably altered by this transformation.

The material used for the study was a gift of Dr. Mike Swain from CSIRO in Australia. This material was evaluated because it has been extensively characterized at Swain's laboratory and elsewhere. The results of our evaluation indicated that at ambient temperature, this ceramic matrix composite acts very much like a metal, in that it has a threshold for fatigue crack growth, crack growth was discontinuous at low ΔK, and cracks were observed to lengthen through the formation and breakdown of what appeared to be a slip line; the same mechanism as found for aluminum and titanium alloys. Periodic crack arrest markings (striations) were found on the fracture surface, although they had a different appearance than for metallic alloys. A previously developed model for fatigue crack growth was used to derive the low cycle fatigue and stress-failure (S-N) curves, and a good comparison was made with measured S-N curves. For metals, the slope of the crack growth rate curve with increasing ΔK is 2-6, but for PSZ, the slope was found to be 25.

At elevated temperature, the range of ΔK over which stable fatigue crack growth occurred was decreased and the slope of the fatigue crack growth rate curve was increased. The higher the temperature, the smaller the range of fatigue stable crack growth and the lower the fracture toughness; extrapolating tests at 450 and 650°C indicated that by 700-750°C, no stable region of crack growth would be expected, with a K_c of only about 3 MPa$\sqrt{m}$. It was possible also for this material to account for the level of K_c measured by computing the work done in forming the "plastic" zone at fast fracture from the measured strain distribution.

The mechanism responsible for the apparent plasticity exhibited by this material is transformation of monoclinic zirconia to tetragonal, rather than the generation and motion of dislocations as is the case for the aluminum alloy composites studied. Although PSZ is classified as a ceramic, it is certainly unique amongst ceramics, and it is doubtful that the fracture characteristics of this material resemble those of the more typical ceramics, such as the oxides.

Conclusion: Partially stabilized zirconia is very "metal like," exhibiting the same mechanism for fatigue crack growth as an aluminum alloy matrix composite reinforced with SiC or alumina. Temperature effects indicate that this behavior is directly related to the transformation characteristics of the reinforcement. "True fatigue behavior" was exhibited by this material.

B. SILICON NITRIDE REINFORCED WITH SCS-6 CONTINUOUS FIBERS

A small panel of Si_3N_4 matrix reinforced with 4 layers of SCS-6 fibers at a volume fraction level of about 35% fibers was purchased from Textron Speciality Materials Co. The matrix was consolidated around the fibers from powders by relatively standard hot pressing procedures. Several center notched specimens were machined from the panel and tested at ambient temperature. The specimens were difficult to fabricate because of the non-conducting matrix and the tough fibers: it was difficult to find a notching technique and no entirely satisfactory method was ever found for attachment of loading tabs.

Testing of this composite is still in progress, but the overall result obtained to date indicates that cracking is similar in some ways to the titanium matrix material in that crack bridging is the principal mechanism of damage tolerance. This material definitely exhibits an S-N behavior: at high

applied stress, the number of cycles to fracture are few, while at low stress, the number of cycles are many.

> **Conclusion:** Fiber strength and fiber interface strength control the damage tolerance of both metal and ceramic matrix continuous fiber composites. The question remains as to whether the same fracture mechanics approach may be used to describe fatigue crack growth in this family of composites as was used successfully for the metal matrix materials.

C. GLASS-CERAMIC MATRIX REINFORCED WITH NICALON FIBERS

The tensile and fracture properties of these composites were measured at ambient temperature and 800°C for two industrial sponsors. The part of that work performed for GE Aeroengines is in the process of publication [19]. The material, manufactured by Dow Corning Corporation, consists of a calcium alumino silicate glass reinforced with about 35% of Nicalon (≈ 12 μm diameter) fibers.

This material fractures in fatigue unlike the other composites studied; it was not possible to initiate and grow a singular dominant crack from a stress concentration. For unnotched specimens cyclically loaded at 25°C, at a level that just initiated matrix cracking, numerous cracks were initiated as cycling continued and crack opening displacement slowly increased, particularly for one of the cracks, until fracture occurred. A higher level of stress caused fracture by approximately the same mechanism in fewer cycles. A stress-failure (S-N) behavior similar to metals resulted, but with a very shallow slope. At 800°C, the damage tolerance for this material is much lower, and fracture occurred much more suddenly with little matrix cracking or fiber pull-out observed.

All efforts to initiate and grow a crack from a notch resulted in the formation of cracks along the matrix-fiber interface perpendicular to the notch. Even Mode III loading of the notch gave the same result.

> **Conclusion:** Fatigue behavior at ambient temperature is the result of gradual (cyclic) fiber pull-out once the matrix has cracked. A relatively weak matrix-fiber interface with good frictional properties is required for this behavior. At 800°C the interface is so weak and exhibits so little friction that fiber pull out occurs very rapidly and fatigue properties are greatly degraded.

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